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WADC TECHNICAL REPORT 55-150
PART 3
ASTIA DOCUMENT No. AD 97212

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MATERIALS-PROPERTY-DESIGN CRITERIA FOR METALS

Part 3. Fatigue Evaluation of Magnesium Alloys

W. S. HYLER

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BATTELLE MEMORIAL INSTITUTE

116

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MATERIALS LABORATORY
CONTRACT No. AF 33(616)-2303
PROJECT No. 7360

WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Carpenter Litho & Prtg. Co., Springfield, O.
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FOREWORD

This report was prepared by Battelle Memorial Institute, Columbus, Ohio, under Contract No. AF 33(616)-2303. The investigation was initiated under Project No. 7360, "Materials Analysis and Evaluation Techniques", Task No. 73605, "Design Data for Metals", and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center with Mr. D. A. Shinn acting as project engineer.

This report covers work conducted from October, 1954 to June, 1955.

ABSTRACT

WADC Technical Report 55-150, "Materials-Property-Design Criteria for Metals", indicated that the ANC-5 document shows discrepancies in fatigue data for various magnesium alloys as obtained in rotating-bending, plate-bending, and axial-loading fatigue tests. A study was made of three magnesium alloys FS-1a (AZ31A-0), J-1 (AZ61A-F), and O-1 (AZ80A-F) under conditions of completely reversed stress for the three kinds of loading.

Results suggest that the discrepancies noted in ANC-5 data between rotating-beam fatigue data and data from the other two types of tests are real. Certain other inconsistencies in the data suggest that additional fatigue studies should be made to provide more reliable information.

A review of methods of presenting fatigue data in ANC-5 was made. It is suggested that a more consistent method of presentation be followed for the various alloy systems for which fatigue data are reported.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

M. R. WHITMORE
Technical Director
Materials Laboratory
Directorate of Research

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INTRODUCTION

The WADC Technical Report 55-150, "Materials-Property-Design Criteria for Metals", points out that the ANC-5 document lists fatigue data obtained for magnesium alloys by rotating-bending, plate-bending, and axial-loading tests. Examination of the information in the document shows for a number of magnesium alloys that fatigue limits obtained by the various tests for the same load ratio showed wide divergence.

Two possibilities were enumerated to explain these inconsistencies:

(1) Data appearing in ANC-5 on the fatigue limits of magnesium alloys were questionable.

(2) Data appearing in ANC-5 on the fatigue limits of magnesium alloys were not questionable, in that stress gradient and other considerations have a marked influence on the fatigue behavior of some materials and less influence on the fatigue behavior of other materials.

This task was introduced in an effort to determine whether or not the information in ANC-5 reflects actual material fatigue properties.

This report summarizing the results of this program is being published for information. The opinions expressed are not necessarily those of the Air Force or of the ANC-5 Panel. The report is issued to serve as a basis for discussion and future action concerning possible changes in the ANC-5 document.

MATERIALS

The three materials used in this investigation were selected to provide a wide range of fatigue properties under the various types of test as shown in ANC-5. Table 1 illustrates some of the fatigue data obtained by different methods of testing various magnesium alloys as set forth in the ANC-5 document.

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After examining the data in the table, FS-1a (AZ31A-O) sheet material was selected for axial-loading and plate-bending tests. The other two materials, J-1 (AZ61A-F) and O-1 (AZ80A-F) extruded alloys, were chosen for fatigue evaluation in rotating bending, plate bending, and axial loading. These alloys appeared to have some of the largest differences in fatigue strength obtained from the various types of tests.

The FS-1a (AZ31A-O) material was received in a 1/4-inch-thick sheet, 30 by 48 inches, from the A. R. Purdy Company, Lindhurst, New Jersey. Metallographic examination of the structure was employed to determine the direction of rolling but little difference was observed in grain size or shape in the two possible rolling directions. To supplement this evidence, tensile properties were evaluated from specimens oriented in the two directions. These properties were essentially the same in both directions. It was decided, therefore, to use the 48-inch direction for the longitudinal axis of the specimens. The sheet was sectioned in this manner and individual coupons were given a stress relief treatment (500 F for 15 minutes, followed by air cooling).

Metallographic study of the structure before and after stress relief showed the treatment did not affect the structure except that some twin lines developed during stress relief.

Hardness examinations were made on the material before and after it was stress relieved with both measurements leading to the same result, a Vickers D.P.H. number of 58 with a 2.5-kilogram load.

Spectrographic analysis of the FS-1a (AZ31A-O) showed that the composition of this material fell within the range specified by the American Society for Metals.

The O-1 (AZ80A-F) and J-1 (AZ61A-F) materials were each received from the Aluminum Company of America in the form of three strips 5/8 by 3-1/2 inches by 10 feet long. Preliminary samples were taken from both materials for metallographic, spectrographic, and tensile tests.

The metallographic examination showed that grain size and shape for both materials were comparable to those appearing in the structure of FS-1a (AZ31A-O).

The spectrographic analysis also showed that the constituents of the two alloys were within the composition limits specified by the American Society for Metals for these alloys. However, the analysis also showed the two materials to have been interchanged. This was not discovered until the specimens had been rough sawed and heat treated as suggested by ASM Metals Handbook for each alloy. In the case of the O-1 (AS80A-F) material, it was possible to heat treat again at the correct temperature. Specimens of each alloy were given, therefore, the same heat treatment — 2 hours at

750 F followed by air cooling. Specimens were stress relieved for 1/4 hour at 600 F and air cooled.

Table 2 compares the results of the laboratory tensile tests on the three magnesium alloys with the ANC-5 values. A brief inspection of the data shows that the strength and ductility of the alloys are above the design mechanical properties as shown in ANC-5.

On the basis of this study, the three magnesium alloys conformed to the appropriate AMS specifications.

SPECIMEN DESIGN AND PREPARATION

The specimens of FS-1a (AZ31A-O) sheet were sawed out parallel to the 48-inch direction and then stress relieved as previously described.

The bars of O-1 (AZ80A-F) and J-1 (AZ61A-F) were sawed to length and then, for the plate-bending and axial-loading specimens, were split by sawing to yield two pieces per length about 5/16 by 3-1/2 inches in cross section. The rotating-beam specimen blanks were obtained by sawing the appropriate lengths into four pieces 5/8 by 7/8 inches. All the material then was heat treated as described in the previous section. Since many of the flat pieces warped during heat treatment, they were straightened by the stress relief treatment between clamped plates.

Rotating bending specimens were standard R. R. Moore specimens with a continuous-radius test section, and having a minimum diameter of 0.300 inch. Plate-bending specimens were a modified constant-stress specimen. Instead of the usual triangular test section, a continuous-radius (6-inch radius) test section was employed. The specimen thickness after polishing was 0.235 inch. Axial-loading specimens also had a continuous-radius test section (12-inch radius). The middle 4-3/4 inches of the specimen was milled and polished to 0.172-inch nominal thickness. Following machining, all surfaces of the test sections were polished with 400-grit and 600-grit emery paper.

FATIGUE MACHINES

The rotating bending fatigue tests were performed in standard R. R. Moore testing machines. The capacity of these machines is a bending moment of 200-inch-pounds; the speed is variable up to about 10,000 cycles per minute.

The machine used for the plate-bending tests was a Krouse testing machine. The load capacity of this machine at the cam is 150 pounds; the operating speed is 1,725 cycles per minute.

Krouse axial-load testing machines of 5,000-pound and 10,000-pound capacities were used to subject the specimens to reversed axial loading. The speeds employed were 1,500 and 1,100 cycles per minute, respectively. The specimens were supported by guide plates on either side of the specimen to prevent buckling under the compressive load. Sheet Teflon liners on the guide plates eliminated damage to the specimen by fretting and galling.

Before testing started, each machine was calibrated under both static and dynamic conditions.

FATIGUE RESULTS

In each kind of fatigue test, specimens were tested under completely reversed stress. Thus, the data from each kind of test should be comparable with that of the other fatigue tests performed. The program was intended as a limited study to determine, in general, whether the wide discrepancies in data from one test to another, such as reported in ANC-5, were real. The number of specimens generally employed in any one test was nine. Usually three specimens were tested at each of several stress levels to provide data for a range in lifetime from about 10,000 cycles to 10,000,000 cycles.

Results of the study are presented in Table 3, for FS-1a (AZ31A-O); Table 4, for J-1 (AZ61A-F); and Table 5, for O-1 (AZ80A-F).

These data are plotted on stress-log lifetime coordinates in Figures 1 through 8. Indicated also on these figures when available are:

(1) S-N curves (solid lines) constructed from information in ANC-5.

(2) Scatterbands (bordered by dotted lines) for data obtained on the various alloys from Dow Chemical Company. Such information was obtained from plate-bending and rotating-bending fatigue. No information relating to axial-load fatigue behavior was obtained for the three magnesium alloys studied.

Fatigue limits at 10^7 cycles were estimated for each alloy and test on the basis of the limited data obtained in this program. These are listed in the following tabulation together with appropriate values obtained from

Tables 4.112 (a) to (c) of ANC-5 Bulletin and also minimum values obtained from the scatterbands representative of the Dow Chemical Company data.

Material	Type Test	Fatigue Limit, 10^7 cycles, R = 1.0		
		ANC-5	Experimental	Dow
FS-1a	Axial loading	8,000	12,000	—
(AZ31A-O)	Plate bending	14,500	12,000	13,000
J-1	Axial loading	13,500	14,000	—
(AZ61A-F)	Plate bending	11,500	10,000	10,000
	Rotating bending	20,500	20,000	17,500
O-1	Axial loading	—	12,000	—
(AZ80A-F)	Plate bending	12,500	10,000	12,500
	Rotating bending	22,500	22,000	20,500

From the tabulation it appears that the major discrepancy in rotating-bending fatigue values with those from the other two types of test as appears in ANC-5 are substantiated. With regard to the other two types of fatigue tests, the following comments apply:

(1) Fatigue limits in axial loading and plate bending for FS-1a (AZ31A-O) appear to be the same. This is considerably different than is reported in ANC-5 for this alloy.

(2) The 20 per cent difference in fatigue limits between axial-load and plate-bending tests for J-1 (AZ61A-F) appears to be reasonably substantiated. In this limited experimental study, the discrepancy in fatigue limit values is somewhat greater than that reported in ANC-5.

(3) Information for O-1 (AZ80A-F) magnesium alloy for axial loading was not available in ANC-5. The experimental work suggests there is approximately 20 per cent difference between axial-loading and plate-bending fatigue limits.

(4) In general, fatigue limits obtained by experiment or reported in ANC-5 are on the low portion of the scatter band characteristic of Dow Chemical Company data.

DISCUSSION

Discrepancies in Fatigue Data

From the results of the limited experimental program it appears that some of the discrepancies in fatigue values in ANC-5 [Tables 4.112 (a) to (c)] stem from actual differences in behavior of the three magnesium alloys as related to type of test. Other discrepancies suggest some of the data to be questionable.

With regard to this latter statement, information in Tables 4.112 (a) to (c) on die-cast, sheet, extrusion, and forging alloys were re-examined based on the following assumptions related in part to the limited experimental data:

(1) Rotating-bending fatigue strengths of the various magnesium alloys are appreciably greater than fatigue strengths obtained by plate-bending and axial-loading tests.

(2) Fatigue strength of the materials obtained by plate-bending and axial-loading tests are nearly equal.

(3) For any kind of fatigue test, the fatigue strengths of any one material, whether extruded or forged, are nearly equal.

(4) Fatigue behavior of O-1A (AZ80A-T5) and O-1HTA (AZ80A-T5) are about the same.

From these assumptions and from the experimental results, fatigue information in Tables 4.112 (a) to (c) on the following alloys and tests appears questionable:

Alloy	Condition	Type of Test
M (M1A-F)	Extrusion	Rotating bending
M (M1A-F)	Forging	Plate bending
Ma (M1A-O)	Sheet	Axial loading
FS-1a (AZ31A-O)	Sheet	Axial loading
O-1HTA (AZ80A-T5)	Forging	Rotating bending
O-1HTA (AZ80A-T5)	Extrusion	Axial loading

The question of difference (for one material) in fatigue limits observed for rotating bending in comparison with plate-bending and axial-loading fatigue is of more academic interest. If these differences occur

(and they appear real in regard to the magnesium alloys studied) the suggestion that rotating-bending fatigue-test data be eliminated from ANC-5 (WADC Technical Report 55-150, Part 1, pp 63) appears valid, since, in general, service-stress applications in airframe structures more nearly approach sheet or plate bending or axial loading. Another possibility would be to include a precautionary note regarding the use of rotating bending data.

A number of factors may contribute to this difference in behavior. These might include surface effects associated with slight differences in specimen preparation, speed effects — as related to modulus, stress gradient effects, and the notch effect of the sharp corners of the plate and sheet specimens. This latter factor may not be too important since examination of failures of sheet and plate specimens did not show any decided tendency for failures to nucleate at the corners. Resolution of these differences probably can be made with experimental study. It was beyond the scope of the present study, however.

Presentation of Fatigue Data in ANC-5

Fatigue data for aluminum alloys are presented in ANC-5 in three forms: (1) graphical, as stress range diagrams (Goodman-type diagrams), (2) graphical, as S-N scatterbands, and (3) tabular. The stress-range diagram of Figure 3.122 (f) shows constant lifetime lines representative of the lower edges of the scatterbands. The data presented in tabular form are considered as average values, lying at about the center of the scatterbands presented in Figures 3.112 (a) to (e).

As shown in Figures 2, 4, 5, 7, and 8 of this report, many of the stress-lifetime values tabulated in ANC-5 for magnesium alloys [Tables 4.112 (a) to (c)] lie on the lower edge of the scatterbands representing data from the Dow Chemical Company. This is particularly noticeable for stresses involving short lifetimes.

It would appear desirable from the standpoint of clarity to aircraft designers to present fatigue information for all materials (aluminum alloys, magnesium alloys, steels) in a similar manner.

One method of reporting fatigue data in ANC-5 to provide consistency in presentation is outlined. Sufficient data appear to be available for many aluminum and magnesium alloys to permit statistical analysis. Such data, when available, could be so analyzed for insertion in ANC-5. For example, it would be possible to compute 50 per cent and 95 per cent probability S-N curves. These would be comparable roughly to average values presently listed in the tables and to the lower edges of the scatterbands presently shown in the figures in ANC-5, respectively.

If this method were adopted, it would be desirable to include in the title of the various tables, or as a footnote to the tables, the fact that listed values represent "50 per cent probability values". With regard to the graphical presentation of S-N scatterbands, curves could be shown and labeled representing 95 per cent, 50 per cent, and 5 per cent probability.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of the limited experimental study of the fatigue behavior of three magnesium alloys and further study of fatigue information currently assembled in ANC-5, the following conclusions and recommendations appear warranted:

(1) The fatigue limits of some magnesium alloys tested in rotating-bending appear significantly higher than fatigue limits obtained from plate-bending and axial-loading tests. In aircraft structures, components rarely are subjected to rotating bending, therefore, it is recommended: (1) that a precautionary note be added to tables containing rotating-bending data on magnesium alloys concerning their limited design use, or (2) that rotating-bending fatigue information be eliminated from ANC-5.

(2) Certain inconsistencies appear in fatigue information for magnesium alloys (not related to Item 1 above) listed in Tables 4.112 (a) to (c) of ANC-5. It is recommended that a program be initiated to investigate discrepancies in the following cases:

Alloy	Condition	Types of Test
M (M1A-F)	Extrusion	Rotating bending
M (M1A-F)	Forging	Plate bending
Ma (M1A-O)	Sheet	Axial loading
FS-1a (AZ31A-O)	Sheet	Axial loading
O-1HTA (AZ80A-T5)	Forging	Rotating bending
O-1HTA (AZ80A-T5)	Extrusion	Axial loading

It appears desirable to make such an investigation employing several heats of each material to provide information of more general applicability.

(3) The presentation of fatigue information in ANC-5 for aluminum alloys is not the same as for magnesium alloys. It is recommended for consistency and clarity, that a uniform method of presenting such data be adopted. A suggested method might be:

(a) Tabular presentation as stress for various lifetimes. The stress values could represent 50 per cent probability values as determined from statistical analysis.

(b) Graphical presentation of S-N curves of 95 per cent, 50 per cent, and 5 per cent probability.

(c) Graphical presentation as stress range diagrams (Goodman-type diagrams) showing constant lifetime curves typical of the various materials.

TABLE 1. FATIGUE STRENGTHS OF VARIOUS MAGNESIUM ALLOYS OBTAINED FROM DIFFERENT METHODS OF FATIGUE TESTING (FROM ANC-5)

Designation	Type of Fatigue Test	Fatigue Strength at Indicated Number of Cycles (Mean Stress = 0), ksi 10^5	10^6	10^7
	Sheet Alloy			
Ma (M1A-O)	Plate bending	15.5	12.0	10.0
	Axial loading	9.0	6.0	6.0
Mh (M1A-H24)	Plate bending	18.5	14.0	11.0
	Axial loading	17.0	14.0	14.0
FS-1a (AZ31A-O)	Plate bending	15.5	15.0	14.5
	Axial loading	10.5	8.5	8.0
FS-1h (AZ31A-H24)	Plate bending	18.0	16.0	15.5
	Axial loading	14.5	14.0	14.0
	Extruded Alloy			
O-1HTA (AZ80A-T5)	R. R. Moore	27.0	24.5	22.5
	Plate bending	19.0	16.0	13.0
	Axial loading	38.0	31.5	25.5
J-1 (AZ61A-F)	R. R. Moore	24.5	22.5	20.5
	Plate bending	17.5	12.0	11.5
	Axial loading	17.5	13.5	13.5
M (M1A-F)	R. R. Moore	15.5	13.0	10.5
	Plate bending	14.0	11.0	10.0
	Forged Alloy			
J-1 (AZ61A-F)	R. R. Moore	27.5	24.5	21.5
	Plate bending	16.5	12.5	12.0
O-1HTA (AZ80A-75)	R. R. Moore	26.0	21.0	16.0
	Plate bending	18.0	14.5	14.0
	Die Cast Alloy			
R (AZ91A)	R. R. Moore	17.5	16.0	15.0
	Plate bending	10.5	9.0	8.0

TABLE 2. TENSILE PROPERTIES OF THREE MAGNESIUM ALLOYS

Property	FS-1a (AZ31A-O)		O-1 (AZ80A-F)		J-1 (AZ61A-F)	
	Experi-mental	ANC-5	Experi-mental	ANC-5	Experi-mental	ANC-5
Ultimate Tensile Strength, psi	36,800	32,000	48,400	43,000	44,900	38,000
Yield Strength (0.2 Per Cent Offset), psi	22,400	15,000	31,200	28,000	28,600	20,000
Elongation, per cent	3.4	12.0	18.1	9	20.0	26.0
Reduction in Area, per cent	44.5	—	18.3	—	17.7	—

TABLE 3. FATIGUE TEST RESULTS ON FS-1a (AZ31A-O) MAGNESIUM ALLOY

Specimen	Maximum Stress, ksi	Fatigue Lifetime, cycles
	Axial Loading	
4-2	16.0	75,800
5-2	16.0	88,000
4-1	16.0	91,500
7-1	14.0	516,000
1-2	14.0	5,930,000
1-1	14.0	10,000,000[a]
2-1	13.0	8,066,000
5-1	13.0	8,260,000
2-2	13.0	10,000,000[a]
	Plate Bending	
3-1	16.0	96,000
3-2	16.0	267,000
6-2	14.0	251,000
6-1	14.0	414,000
7-2	14.0	10,000,000[a]
8-1	12.0	10,000,000[a]
8-2	12.0	10,000,000[a]

(a) This specimen did not fail.

TABLE 4. FATIGUE TEST RESULTS ON J-1 (AZ61A-F) MAGNESIUM ALLOY

Specimen	Maximum Stress, ksi	Fatigue Lifetime, cycles
	Axial Loading	
JA6	22.0	3,300
JA17	22.0	6,600
JA10	20.0	74,800
JA3	18.0	100,000
JA20	18.0	935,700
JA8	16.0	323,100
JA6	16.0	4,113,000
JA20	16.0	6,182,900
JA9	15.0	10,000,000[a]
JA12	14.0	10,000,000[a]
JA13	14.0	10,000,000[a]
	Plate Bending	
JP15	18.0	65,000
JP4	18.0	76,000
JP5	18.0	96,000
JP13	16.0	173,000
JP4-1	16.0	3,236,000
JP9	16.0	4,651,000
JP16	14.0	439,000
JP15	14.0	3,002,000
JP18	12.0	290,000
JP16-1	12.0	370,000
JP9-1	12.0	10,000,000[a]
JP7	10.0	10,000,000[a]
JP18-1	10.0	10,000,000[a]
	Rotating Bending	
JR5B1	28.4	32,000
JR11B1	25.6	63,000
JR20B1	24.7	78,000
JR5B2	24.7	124,000
JR11B2	24.7	153,000
JR11A1	22.0	342,000
JR11A2	22.0	890,000
JR20B2	22.0	2,337,000
JR19A1	20.5	10,000,000[a]
JR19A2	20.5	10,000,000[a]

(a) This specimen did not fail.

TABLE 5. FATIGUE TEST RESULTS ON O-1 (AZ80A-F) MAGNESIUM ALLOY

Specimen	Maximum Stress, ksi	Fatigue Lifetime, cycles
	Axial Loading	
OA12	18.0	1,146,300
OA21	18.0	3,750,000
OA8	18.0	4,604,000
OA10	16.0	1,758,000(a)
OA17	16.0	1,909,000
OA3	16.0	2,245,000(a)
OA20	16.0	3,980,000(a)
OA6	16.0	10,000,000(b)
OA11	16.0	10,000,000(b)
OA13	14.0	4,126,000
OA5	14.0	10,000,000(b)
OA15	12.0	10,000,000(b)
	Plate Bending	
OP15-1	15.0	591,000
OP13	15.0	4,087,000
OP7-1	13.0	672,000
OP16	13.0	925,000
OP9	13.0	10,000,000(b)
OP18-1	13.0	10,000,000(b)
OP15-2	11.0	1,474,000
OP18-2	11.0	10,000,000(b)
OP4	11.0	10,000,000(b)
OP7-2	11.0	10,000,000(b)
	Rotating Bending	
OR5A1	28.2	94,000
OR19A2	27.5	151,000
OR19A1	27.5	152,000
OR5A2	27.5	212,000
OR5B1	24.0	473,000
OR14A1	24.0	812,000
OR14A2	24.0	2,464,000
OR19B1	22.0	10,000,000(b)
OR19B2	22.0	10,000,000(b)

(a) This specimen failed in grip.
(b) This specimen did not fail.

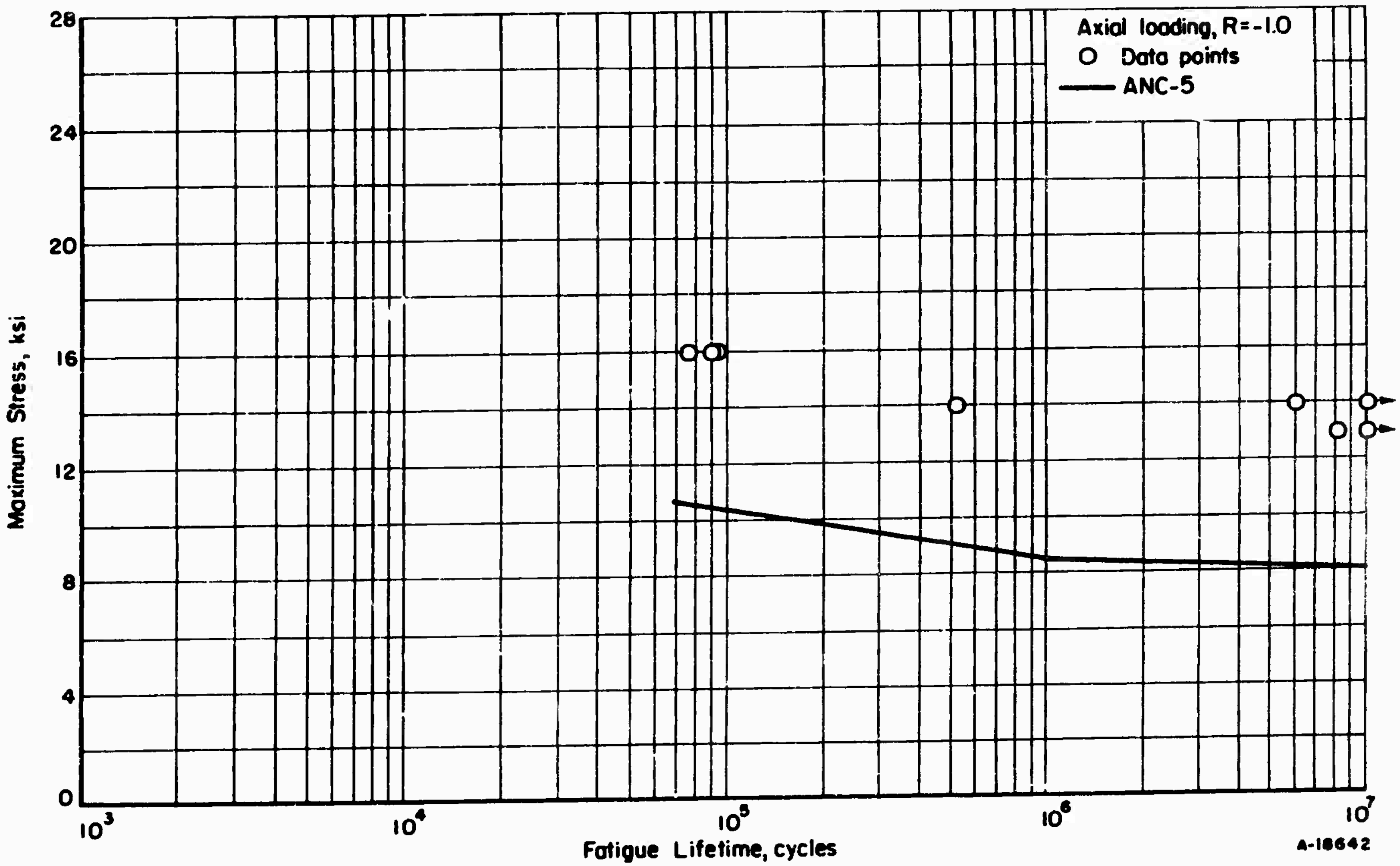

FIGURE 1. FATIGUE TEST RESULTS ON FS-1a (AZ31A-O) MAGNESIUM ALLOY

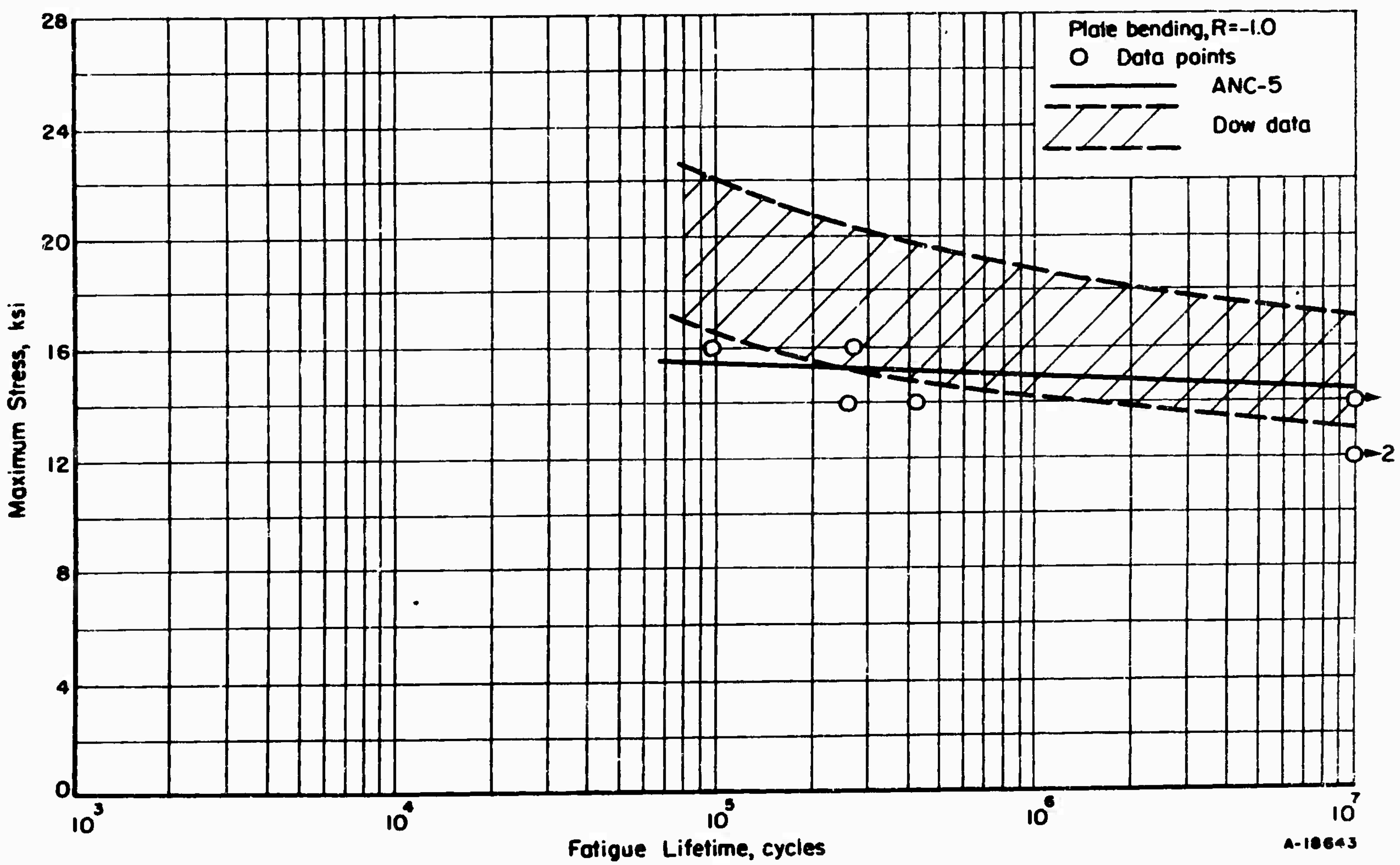

FIGURE 2. FATIGUE TEST RESULTS ON FS-1a (AZ31A-O) MAGNESIUM ALLOY

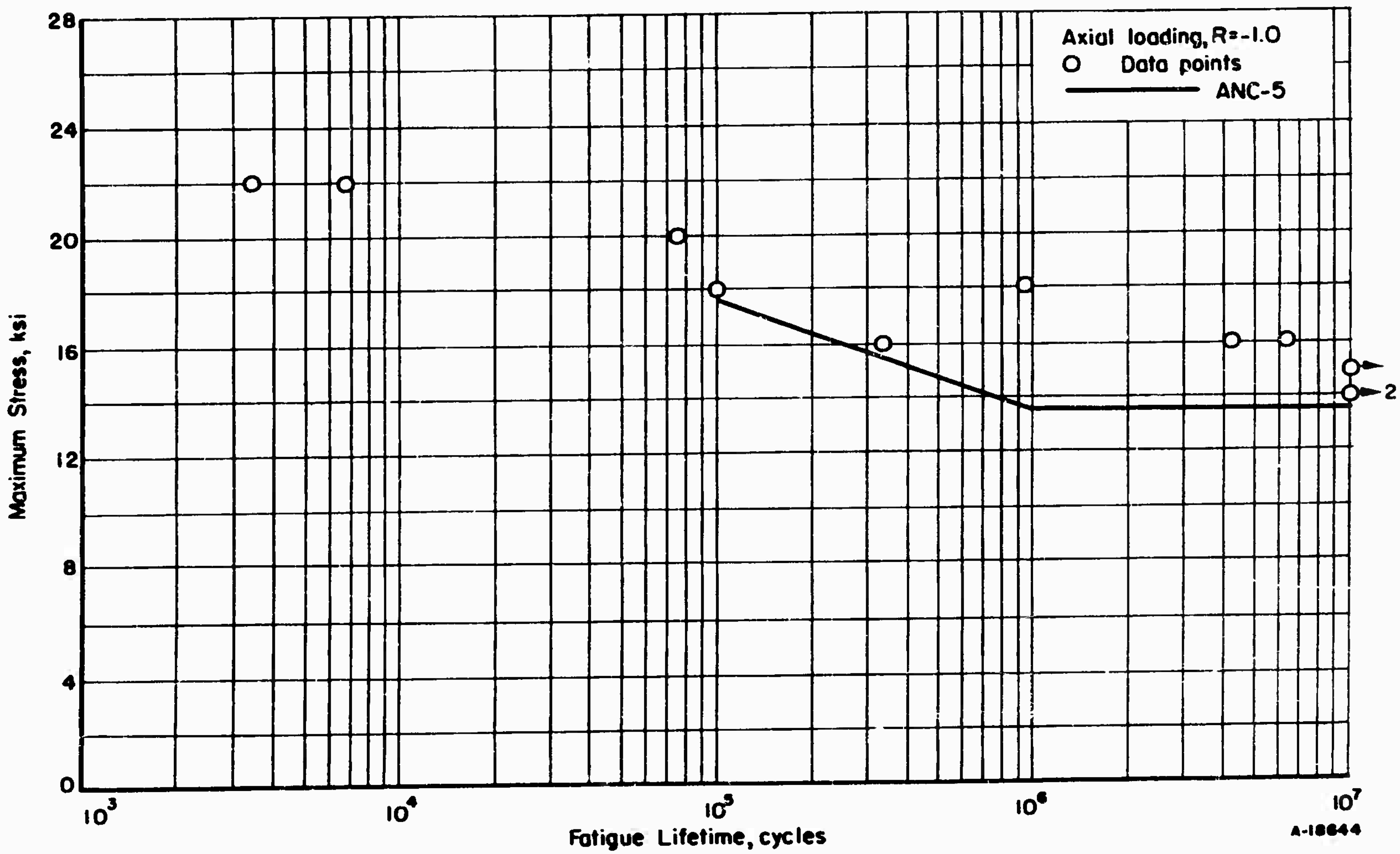

FIGURE 3. FATIGUE TEST RESULTS ON J-1 (AZ61A-F) MAGNESIUM ALLOY

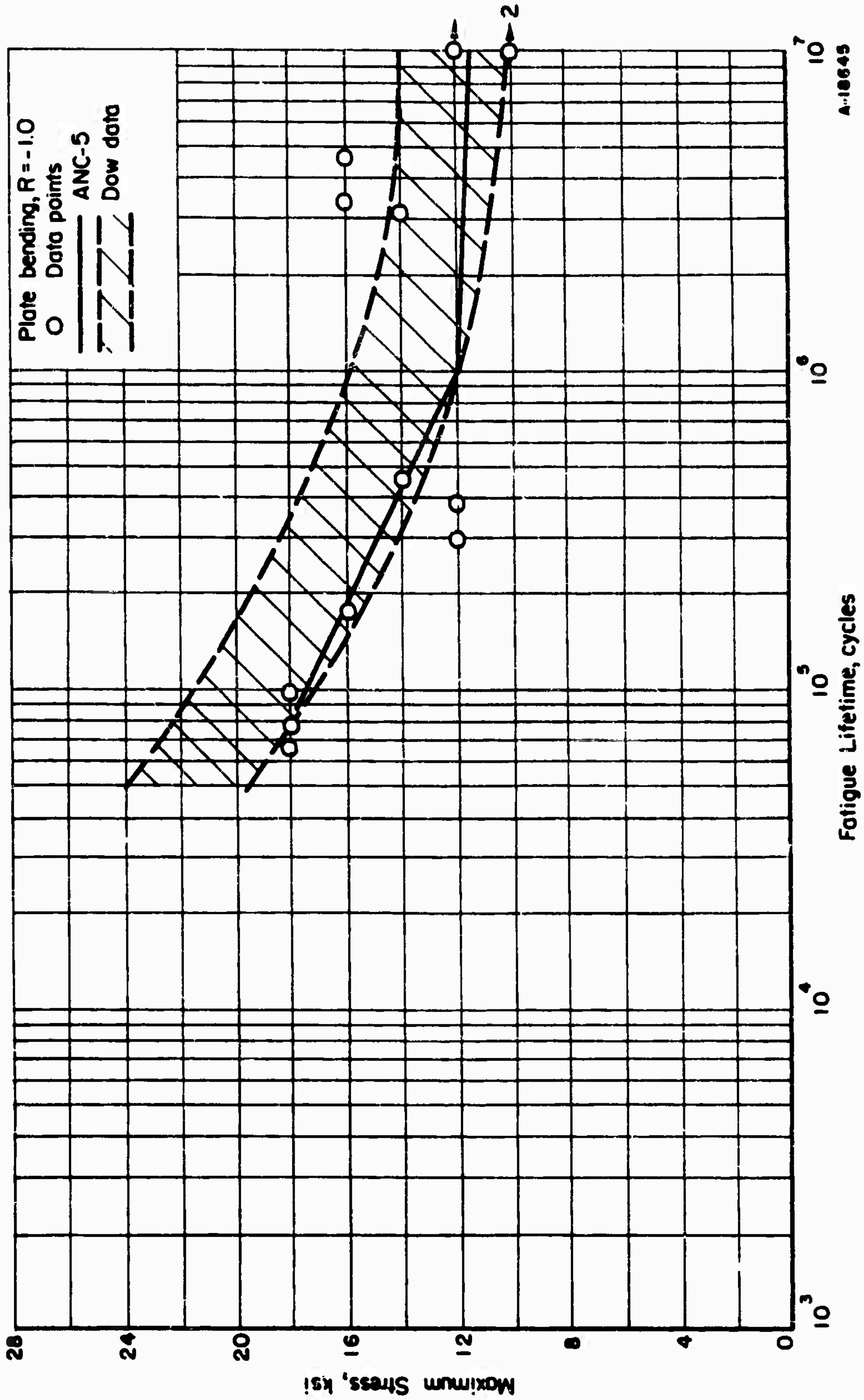

FIGURE 4. FATIGUE TEST RESULTS ON J-1 (AZ61A-F) MAGNESIUM ALLOY

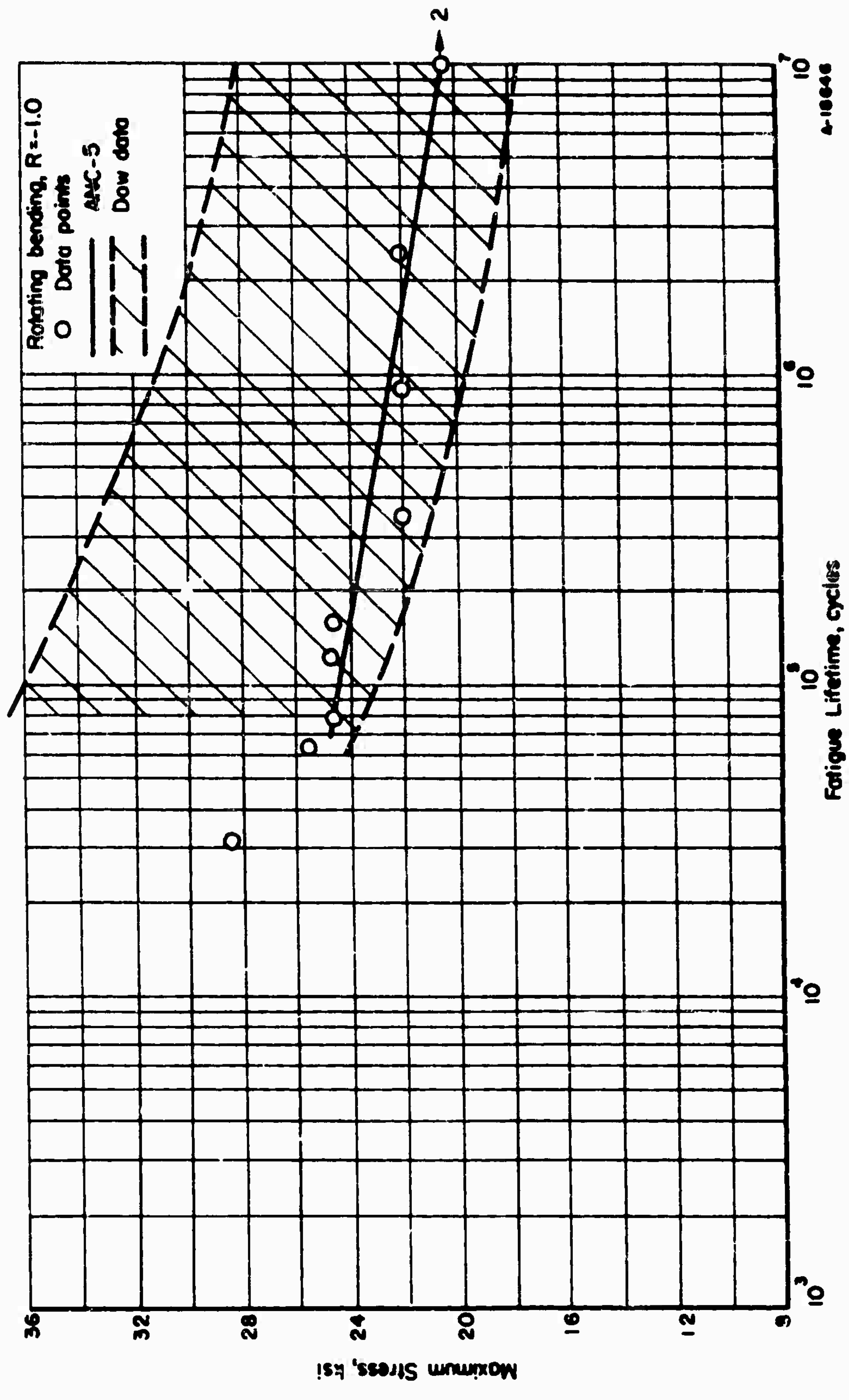

FIGURE 5. FATIGUE TEST RESULTS ON J-1 (AZ61A-F) MAGNESIUM ALLOY

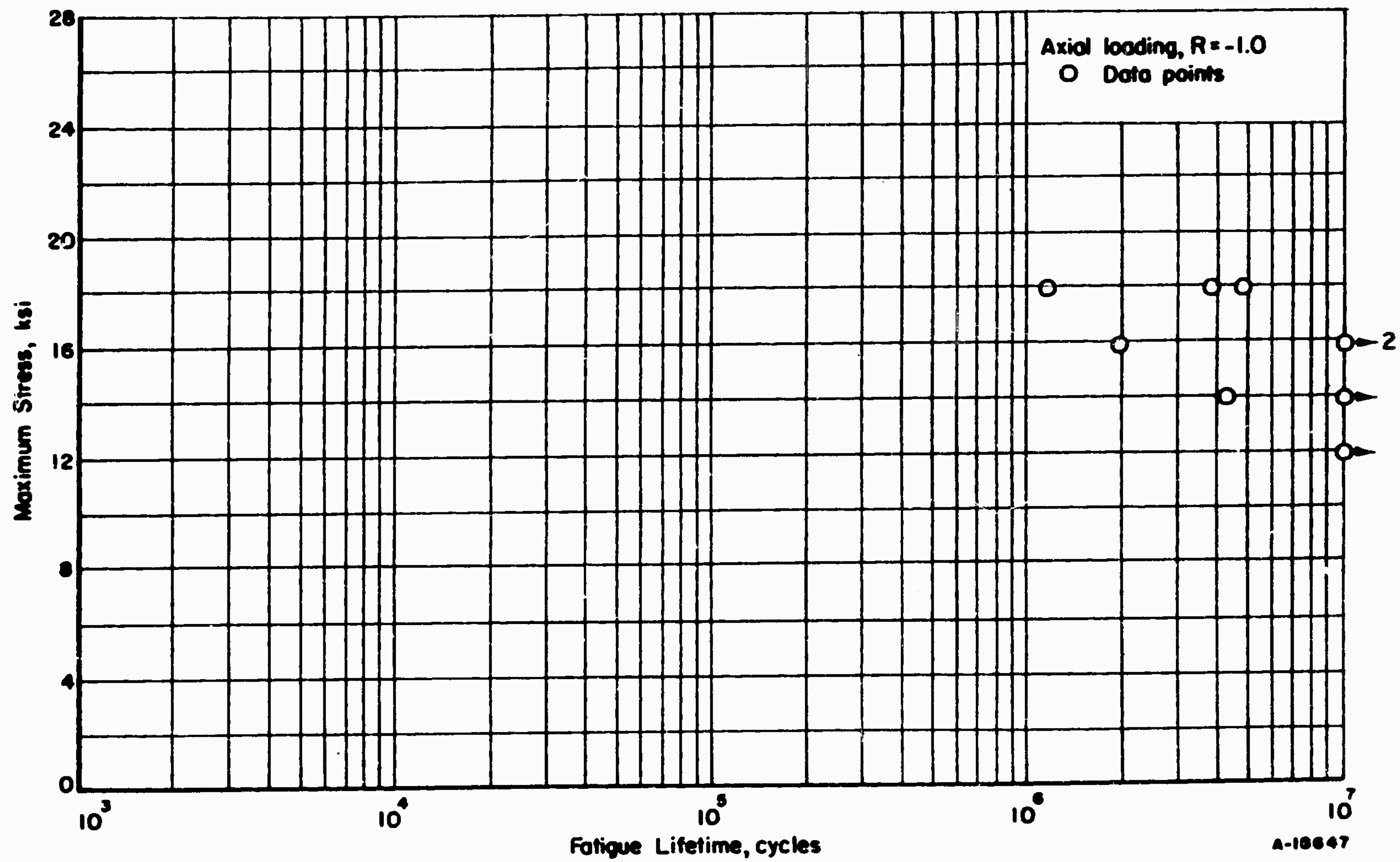

FIGURE 6. FATIGUE TEST RESULTS ON O-1 (AZ80A-F) MAGNESIUM ALLOY

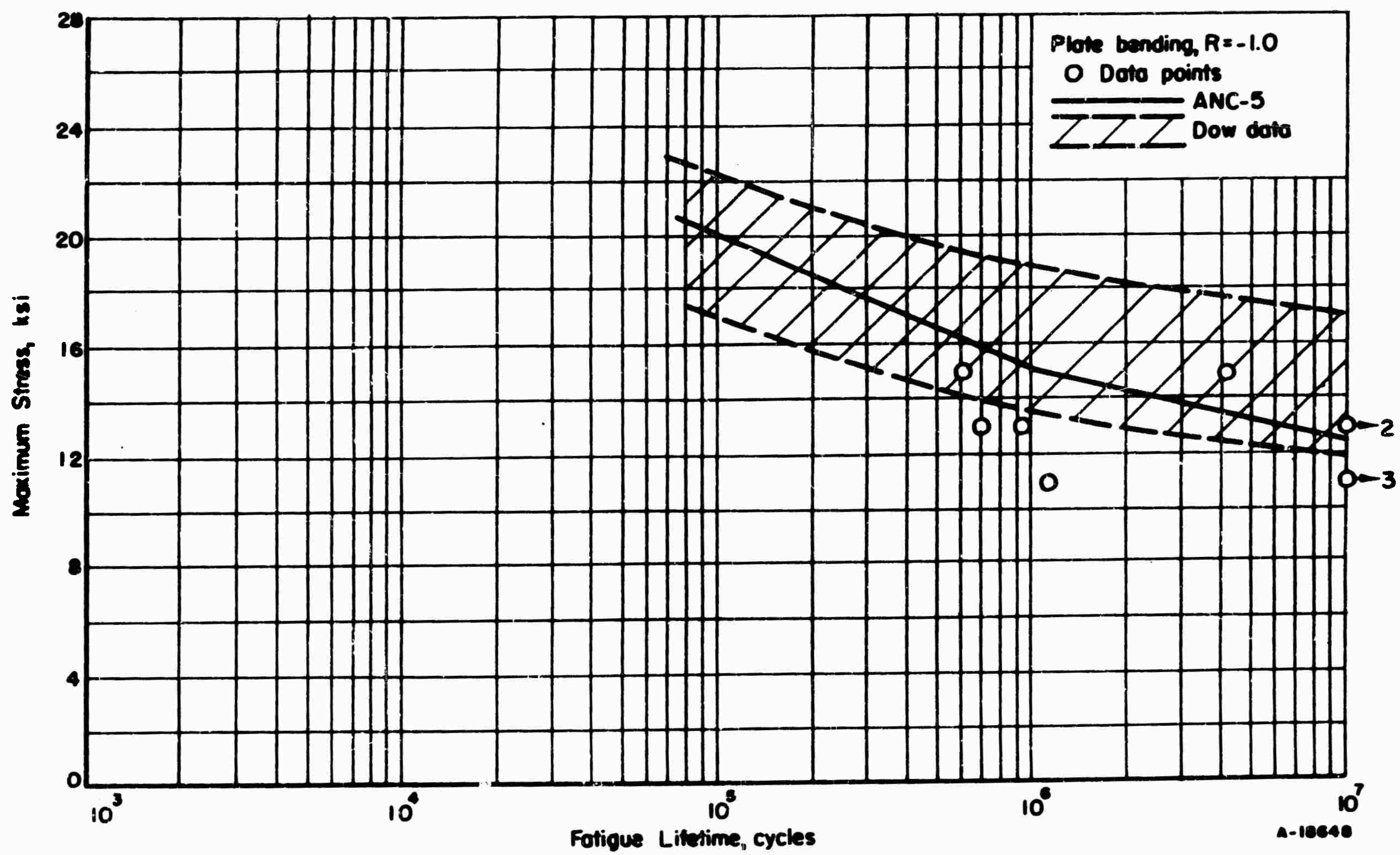

FIGURE 7. FATIGUE TEST RESULTS ON O-1 (AZ80A-F) MAGNESIUM ALLOY

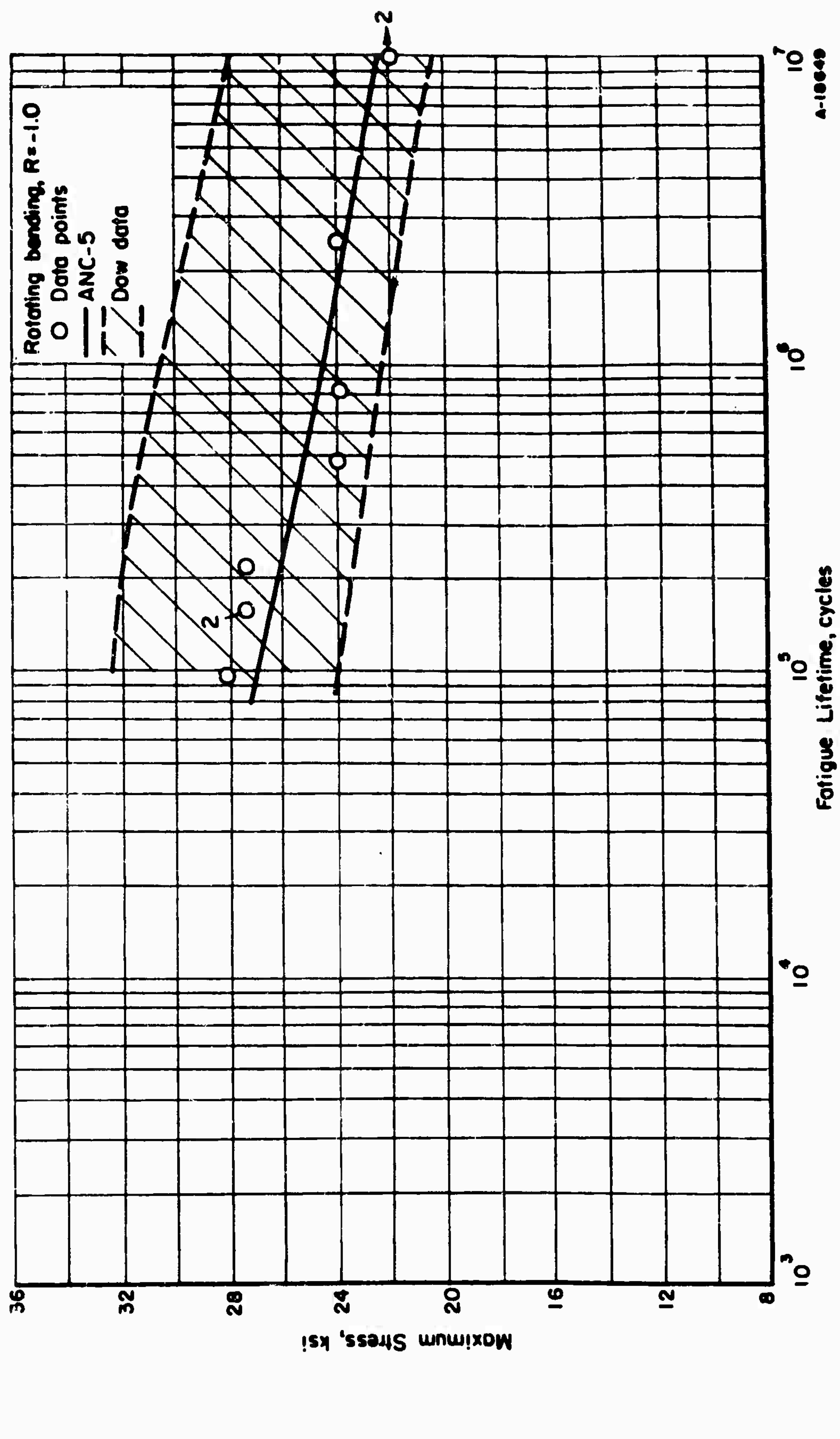

FIGURE 8. FATIGUE TEST RESULTS ON O-1 (AZ80A-F) MAGNESIUM ALLOY